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Capillary and Acceleration Wave Breakup of Liquid Jets in Axial-Flow Airstreams

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Capillary and Acceleration Wave Breakup of Liquid Jets in Axial-Flow Airstreams

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National Aeronautics
and Space Administration

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Summary

Data on mean drop diameter D_m were obtained for the atomization of water jets injected cross stream from simple orifices into axial-flow airstreams. A scanning radiometer was used in obtaining data over an airstream momentum $\rho_a V_r$ range of 3.7 to 25.7 g/cm^2 sec (weight flow per unit area). For low-momentum airstreams values of D_m were correlated with the product of the Weber and Reynolds numbers We Re to give the following expression for capillary wave breakup:

$$\frac{D_o}{D_m} = 0.21(\text{We Re})^{0.25} \qquad \text{for We Re} < 10^6$$

where D_o is orifice diameter, $\text{We} = \rho_a D_o V_r^2/\sigma$, $\text{Re} = D_o V_r/\nu$, V_r and ρ_a are airstream relative velocity and density, respectively, and σ and ν are surface tension and kinematic viscosity of the liquid, respectively. Mean drop diameter data for iso-octane, JP-5 fuel, benzene, carbon tetrachloride, and water were used in deriving the empirical expression.

For high-momentum airstreams values of D_m were correlated with We Re values to give the following expression for acceleration wave breakup:

$$\frac{D_o}{D_m} = 0.027(\text{We Re})^{0.4} \qquad \text{for We Re} > 10^6$$

Thus transition from capillary wave to acceleration wave breakup occurred at We Re = 10^6. Only water jets were used in deriving this empirical expression.

Introduction

An investigation was conducted to determine the effect of airstream momentum on mean drop diameters obtained by atomization of water jets injected cross stream from simple orifices into axial-flow airstreams. Such data are needed to supplement previous theoretical and experimental studies of liquid atomization conducted with capillary wave breakup in low-momentum airstreams in order to extend our knowledge to acceleration wave breakup in high-momentum airstreams. Such knowledge is especially needed in the design of fuel injectors for advanced, high-pressure gas turbine combustors, because the concentrations of oxides of nitrogen in the exhaust gases tend to increase markedly with increasing inlet-air pressure. The investigations made in reference 1 show that such concentrations are directly proportional to the square of the mean drop diameter.

In 1957 a basic investigation of liquid jet breakup in airstreams was conducted at the NACA Lewis Flight Propulsion Laboratory (ref. 2). In this investigation the mean drop diameters of sprays of liquids, including water, JP-5 fuel, and other liquids, were correlated with the product of the Weber and Reynolds numbers. Before this, in 1939, Nukiyama and Tanasawa (ref. 3) had developed an empirical expression for a gas-atomizing or air-assist atomizer in which liquid jet breakup occurred within the nozzle. Although they did not develop a relationship between the Sauter mean drop diameter and the Weber or Reynolds numbers, they did show a break in their data, with a viscous breakup occurring at high liquid flow rates and a turbulent breakup occurring at high airflow rates. Also, more recently, studies by Simmons (ref. 4) and Lorenzetto and Lefebvre (ref. 5) have shown a similar type of break in their data. From this it appeared that the data obtained in reference 2 at NACA were only valid for relatively low-momentum airstreams and had been limited in scope by the time-consuming effort required in photographing, counting, and measuring drops. Thus the present investigation was undertaken to extend our knowledge of liquid jet breakup from relatively low-momentum-airstream conditions to high-momentum-airstream conditions, such as those experienced in gas turbine combustors. This was made possible by the development of a rapid technique for obtaining mean drop diameter data for sprays with a scanning radiometer (ref. 6) developed at this Laboratory.

Water jets produced by multiple-orifice spray bars were injected cross stream into a 7.6-centimeter-inside-diameter duct at a water flow rate of 68.1 liters per hour, and the effect of airstream momentum on mean drop diameter was determined over an airstream momentum $\rho_a V_r$ range of 3.7 to 25.7 g/cm^2 sec (weight flow per unit area). Experimental values of the mean drop diameter were obtained with a scanning radiometer and correlated with the product of the Weber and Reynolds numbers. The resulting empirical expressions were then compared with theoretical predictions and with liquid jet

breakup data obtained from other experimental investigations.

Symbols

C_d	drag coefficient of cylindrical jet in crossflow
D	diameter, cm
D_m	experimental mean drop diameter, cm
D_{30}	volume-number mean drop diameter, $\left(\Sigma n D_d^3 / \Sigma n\right)^{1/3}$, cm
D_{32}	Sauter mean drop diameter, $\Sigma n D_d^3 / \Sigma n D_d^2$, cm
e	constant having value between 0 and 1
J	modified sheltering parameter for capillary waves
K	proportionality constant
L	wavelength, cm
Re	Reynolds number, $D_o V_r / \nu$
V_r	relative velocity (i.e., airstream velocity for crossflow), cm/sec
We	Weber number, $D_o \rho_a V_r^2 / \sigma$
β	Jeffrey's sheltering parameter, ranging from 0 to 1
σ	surface tension of liquid relative to air, dynes/cm
θ	angle that jet axis makes with airstream velocity vector
μ	absolute viscosity, g/cm sec
ν	kinematic viscosity, cm^2/sec
ρ	density, g/cm^3

Subscripts:

a	air
c	critical
d	droplet
j	liquid jet
l	liquid
n	number of drops
o	orifice

Apparatus and Procedure

The apparatus used in this investigation is shown in figure 1. Airflow was drawn from the laboratory supply system at ambient temperature (293 K) and exhausted into the atmosphere. Airflow rate was measured with the air orifice shown in figure 2. The airflow control valve was opened until the desired airflow rate per unit area was obtained. Airflows $\rho_a V_r$ of 3.7, 4.6, 5.5, 6.4, 7.3, 11.0, 14.7, 18.3, 22.0, and 25.7 g/cm^2 sec were studied. Water was then injected into the test section through a spray bar by gradually opening the water flow control valve until the desired water flow rate of 68.1 liters per hour was obtained.

The test section consisted of a 7.6-centimeter-inside-diameter duct 15.2 centimeters in length and mounted with a bellmouth inside a 15.2-centimeter-inside-diameter duct 5 meters in length. Two different spray bars were used in the investigation. A schematic drawing of one of the spray bars consisting

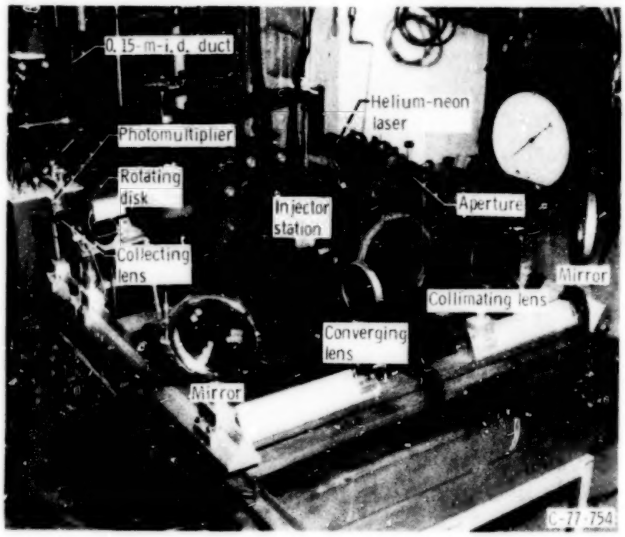

Figure 1. - Apparatus and auxiliary equipment.

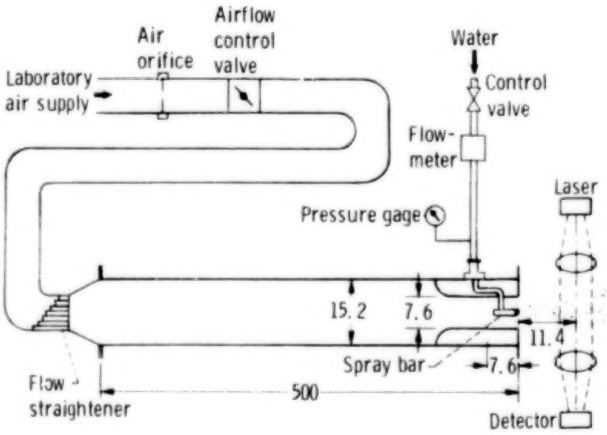

Figure 2. - Test facility and auxiliary equipment. (Dimensions are in centimeters.)

of twelve 0.033-centimeter-diameter orifices is shown in figure 3. A similar spray bar consisting of three 0.132-centimeter-diameter orifices was used to produce relatively large-diameter water jets. The spray bar was positioned at the duct exit, and the water jets were injected cross stream into the axial airflow. Physical characteristics of the spray bars are given in table I.

When the airflow and water flow rates were set, mean drop diameter data were obtained with the scanning radiometer mounted 11.4 centimeters downstream of the open-duct exit. The scanning radiometer optical system shown in figure 4 consisted of a 1-milliwatt helium-neon laser, a 0.003-centimeter-diameter aperture, a 7.5-centimeter-diameter collimating lens, a 10-centimeter-diameter converging lens, a 5-centimeter-diameter collecting lens, a scanning disk with a 0.05- by 0.05-centimeter slit, a timing light, and a photomultiplier detector. More complete descriptions of the scanning radiometer and the method of determining mean particle diameter are given in reference 6. Calibration tests of the instrument were performed as discussed in reference 7.

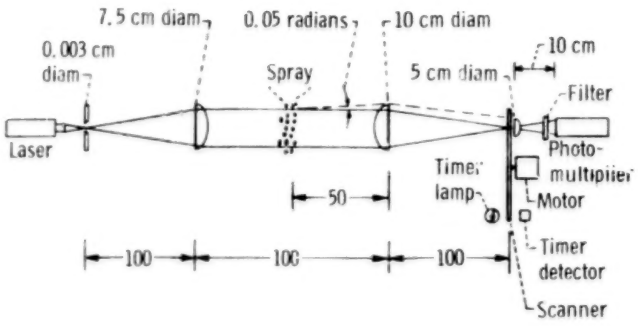

Figure 4. - Scanning radiometer optical path. (Dimensions are in centimeters.)

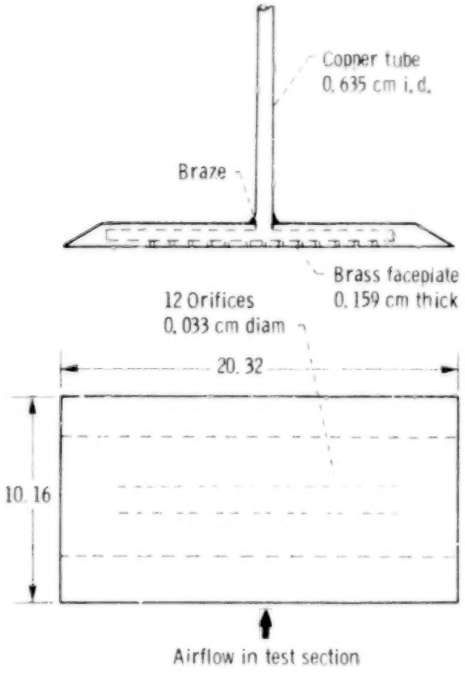

Figure 3. - Schematic diagram of multiple-orifice spray bar. (Dimensions are in centimeters.)

TABLE I.—SPRAY-BAR CHARACTERISTICS

Type of spray	Number of orifices	Orifice diameter, D_o cm	Injection velocity, m/sec[a]
Fine	12	0.023	18.4
Coarse	3	.132	4.6

[a]Measured at a water flow rate of 68.1 liters per hour.

Theoretical Discussion

When a low-velocity liquid is injected into quiescent or "still" air, a Rayleigh type of breakup occurs, as described in reference 8, in which the jet breaks up into lengths of approximately 4.5 times the jet diameter, in which case $D_o/L_c = 0.222$. However, when a liquid jet breaks up in an airstream, the results are quite different. For example, the atomization of a liquid jet in an axial-flow airstream is depicted in figure 5 as a process of forming ligaments from the crests of waves formed on the surface of a liquid jet. The ligaments are then atomized into drops. When the liquid surface is relatively flat, as in the case of fairly large jets produced with a relatively large orifice diameter, Mayer (refs. 9 and 10) predicts that a capillary wave type of breakup will occur. Another type of breakup has been identified by Adelberg (ref. 11), which he defines as acceleration wave breakup. This type of breakup occurs when the ratio of orifice diameter D_o to critical wavelength L_c exceeds the value given by the following expression, which is derived in the appendix:

$$\frac{D_o}{L_c} > 0.127\left|C_D(\sin^2\theta)\right|^{0.5}\mathrm{We}^{0.5} \qquad (1)$$

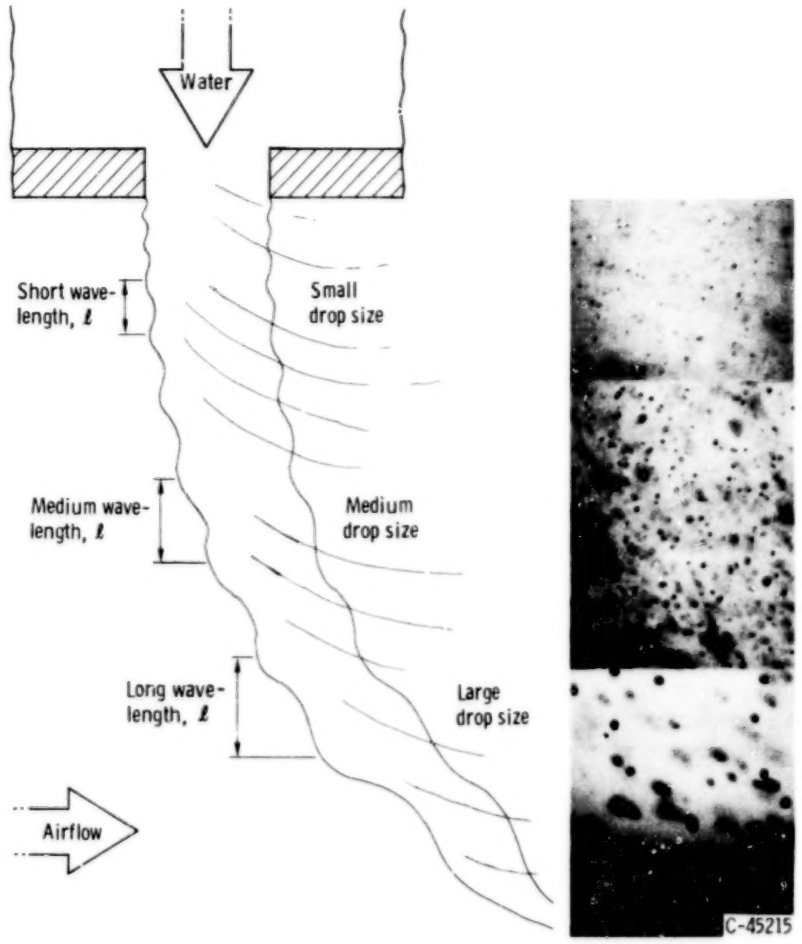

Figure 5. - Schematic of a liquid jet breaking up into ligaments and drops.

where liquid jet diameter is assumed to be approximately equal to orifice diameter D_o, C_d is the drag coefficient, θ is the angle of injection relative to the duct axis, and We is the Weber number. The term D_o/L_c was not investigated in this study since mean drop diameter D_m was used instead of wavelength L to characterize the sprays.

Capillary Wave Breakup

For liquid jet atomization with low-momentum airstreams and low Weber numbers, the wavelength is relatively long and the ratio of D_o/L_c is low. Here a capillary wave type of breakup predominates and from Adelberg's expression the following relationship is derived in the appendix:

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2}\right)^{1/6} \left(\frac{D_o \rho_a V_r^2}{\sigma}\right)^{1/3} \tag{2a}$$

or

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2}\right)^{1/6} \mathrm{We}^{1/3} \tag{2b}$$

Acceleration Wave Breakup

When liquid jet atomization occurs in high-momentum airstreams and Weber numbers are above the critical values given by equation (1), the wavelength is relatively short and the value of D_o/L_c is relatively high. In this case, atomization is predominantly an acceleration wave type of breakup, and from Adelberg's expression the following relationship is derived in the appendix:

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2}\right)^{1/3} \left(\frac{D_o \rho_a V_r^2}{\sigma}\right)^{2/3} \tag{3a}$$

or

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2}\right)^{1/3} \mathrm{We}^{2/3} \tag{3b}$$

Experimental Results

To obtain a better understanding of liquid atomization theory and thereby advance fuel injection technology for gas turbine combustor and augmentor applications, mean drop diameters were determined for sprays produced by cross-stream injection of water jets into axial-flow airstreams. Test conditions covered a water injection velocity range of 4.6 to 18.4 m/sec (table I) and an airstream momentum $\rho_a V_r$ (or weight flow per unit area) range of 3.7 to 25.7 g/cm^2 sec.

Mean drop diameters were determined for water sprays produced by the spray bar shown in figure 3, with relatively small orifice diameters of 0.033 centimeter, and by a similar spray bar with relatively large orifice diameters of 0.132 cm. The effect of airstream momentum (airflow rate per unit area) on mean drop diameter is shown in figure 6, in which the reciprocal of the mean drop diameter is plotted against airstream momentum. Here we see that a marked decrease in the mean drop diameter was obtained as airstream momentum was increased from 3.7 g/cm^2 sec to 18.3 g/cm^2 sec. Also, the small-orifice spray bar gave a considerably finer spray than the large-orifice spray bar. The reciprocal of the mean drop diameter D_m^{-1} was used since it is useful in characterizing a spray in terms of the surface area per unit volume of the spray and can be defined as

$$D_m^{-1} \sim D_{32}^{-1} = \frac{\Sigma n D^2}{\Sigma n D^3}$$

For the coarse spray produced by the large-diameter (0.132 cm) orifices, a transition point occurred at an airstream momentum $\rho_a V_r$ of approximately 4 g/cm^2 sec. Below this transition point the data show that

$$D_m^{-1} \sim (\rho_a V_r)^{0.75} \tag{4}$$

and above this transition point,

$$D_m^{-1} \sim (\rho_a V_r)^{1.2} \tag{5}$$

Similar relationships are shown in figure 6 for fine spray produced by the small-diameter (0.033 cm) orifices. However, in this case, a higher transition point was obtained at an airstream momentum $\rho_a V_r$ of approximately 10 g/cm^2 sec.

In a previous study (ref. 2) it was found that the mean drop size of sprays produced by cross-stream injection of a number of different liquids into airstreams could be correlated with the product of the Weber number and the Reynolds number as follows:

$$\frac{D_o}{D_{32}} = 0.20(\mathrm{We\ Re})^{0.25} \tag{6}$$

where $D_{32} = 1.29\ D_{30}$ as given in reference 2. Thus values of D_o/D_m were plotted against We Re as shown in figure 7. Data for both the large- and the small-orifice-diameter spray bars fall on a single plot of the data, which shows a transition point at a critical We Re value of 10^6.

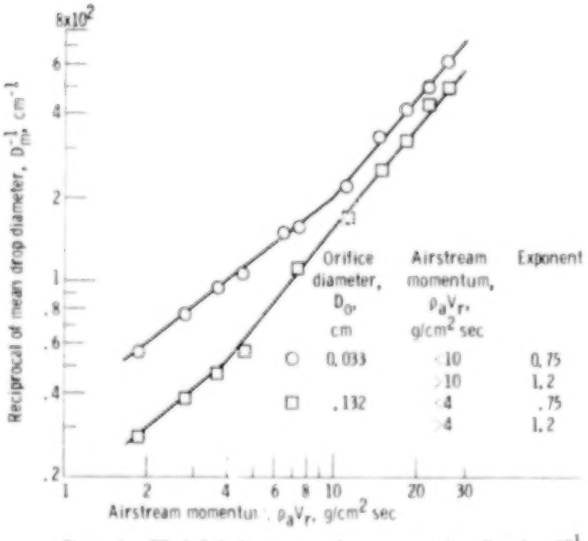

Figure 6. - Effect of airstream momentum on mean drop diameter, D_m^{-1}.

Capillary Wave Breakup

At We Re values below 10^6, the following expression can be written:

$$\frac{D_o}{D_m} = 0.21\left(\frac{\rho_a \rho_l D_o^2 V_r^3}{\mu_l \sigma}\right)^{0.25} \tag{7a}$$

or

$$\frac{D_o}{D_m} = 0.21\,(\text{We Re})^{0.25} \tag{7b}$$

which agrees well with equation (6) since $D_m \sim D_{32}$.

Comparison of the air velocity exponent in equation (7a) with that given in equation (2a), which was derived from a theoretical analysis of capillary wave breakup of liquid jets, indicates that equation (7a) applies primarily to atomization in the regime of capillary wave breakup of liquid jets in a relatively low-momentum airstream. Although equation (7b) has a somewhat smaller exponent for the Weber number than equation (2b) (i.e., 1/4 as compared to 1/3), table II shows that the exponent for relative velocity V_r is not greatly different and the exponent for orifice diameter D_o is the same in each equation.

In table II a listing is given for theoretically and experimentally derived exponents for six different variables as a function of the reciprocal mean drop diameter. The exponents were obtained for the regime of capillary wave breakup of liquid jets in low-momentum axial-flow airstreams. According to equation (7a) the experimentally derived exponents for airstream density and liquid properties all have a value of 0.25, which is within ±32 percent of the theoretical values. Also, the exponents in equation (7a) for airstream density and liquid viscosity are the same as those given for experimental data in reference 12, which also gives liquid density and surface tension each an exponent of 0.38 as compared with 0.25 in equation (7a).

Acceleration Wave Breakup

At We Re values above 10^6 the empirical expression

$$\frac{D_o}{D_m} = 0.027\left(\frac{\rho_a \rho_l D_o^2 V_r^3}{\mu_l \sigma}\right)^{0.4} \tag{8a}$$

or

$$\frac{D_o}{D_m} = 0.027(\text{We Re})^{0.4} \tag{8b}$$

is obtained from figure 7. Comparison of exponents given in equation (8a) with those given in equation (3a), which was derived from acceleration wave breakup theory, shows that equation (8a) is applicable to the acceleration wave breakup of liquid jets in relatively high-momentum airstreams.

The exponents of each variable in equations (3a) and (8a) are given in table III. Theory predicts no effect of orifice diameter on mean drop diameter. However, experimental results obtained in deriving equation (8a) indicate that the reciprocal mean drop diameter varied directly with orifice diameter raised to the -0.2 power. This effect of orifice diameter is small and predicts that, as the orifice diameter approaches zero, the mean drop diameter will also approach zero. This is a more physically realistic prediction than that given by theory. Weiss and Worsham (ref. 13) found that the exponent for orifice diameter had an average value of -0.16. Wolfe and Andersen (ref. 14) studied the breakup of liquid drops behind normal shock waves and obtained an exponent of -0.17 for the initial drop diameter, which compares well with the exponent of -0.2 of equation (8a) for liquid jet breakup.

TABLE II.—EXPONENTS OF PROPERTIES PROPORTIONAL TO RECIPROCAL MEAN DROP DIAMETER D_m^{-1}—CAPILLARY WAVE BREAKUP IN LOW-MOMENTUM AXIAL AIRFLOW

Sources for exponents	Relative velocity, V_r, cm/sec	Orifice diameter, D_o, cm	Air density, ρ_a, g/cm^3	Liquid density, ρ_l, g/cm^3	Surface tension, σ, dynes/cm	Absolute liquid viscosity, μ_l g/cm sec
Theoretical (eq. (2a))	0.67	−0.5	0.33	0.17	−0.17	−0.33
Experimental (eq. (7a))	.75	−.5	.25	.25	−.25	−.25
Kurzius and Raab (ref. 12)	.75	−.38	.25	.38	−.38	−.25

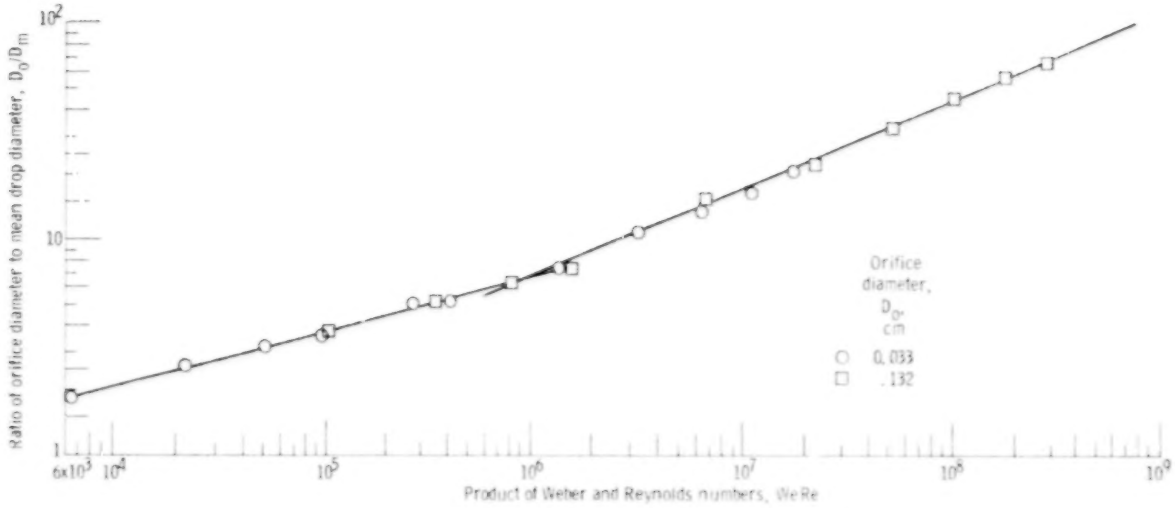

Figure 7. - Relation between orifice-to-mean-drop diameter ratio and Weber-Reynolds number.

TABLE III.—EXPONENTS OF PROPERTIES PROPORTIONAL TO RECIPROCAL MEAN DROP DIAMETER D_m^{-1}—ACCELERATION WAVE BREAKUP IN HIGH-MOMENTUM AXIAL AIRFLOW

Sources for exponents	Relative velocity, V_r, cm/sec	Orifice diameter, D_o, cm	Air density, ρ_a, g/cm^3	Liquid density, ρ_l, g/cm^3	Surface tension, σ, dynes/cm	Absolute liquid viscosity, μ_l g/cm sec
Theoretical (eq. (3a))	1.33	0	0.67	0.33	−0.33	−0.67
Experimental (eq. (8a))	1.2	−.2	.4	.4	−.4	−.4
Nukiyama and Tanasawa (ref. 3)	1.0	0	0	.5	−.5	0
Weiss and Worsham (ref. 13)	1.33	−.16	(a)	.84	−.41	−.34
Lorenzetto and Lefebvre (ref. 5)	1.0	0	.30	.37	−.33	0
Kim and Marshall (ref. 15)	1.14	0	.57	.16	−.41	−.32
Wolfe and Andersen (ref. 14)	1.33	[b] −0.17	.67	.17	−.5	−.33

[a] Used variable $1+\rho_a/\rho_l$.
[b] Exponent for initial drop diameter instead of orifice diameter.

The value of the exponent for reference velocity of 1.2 given in equation (8a) is somewhat less than the theoretical value of 1.33, yet it is somewhat above the value of 1.0 obtained by Nukiyama and Tanasawa (ref. 3) and Lorenzetto and Lefebvre (ref. 5) as listed in table III. Data by Wolfe and Andersen (ref. 14) and by Weiss and Worsham (ref. 13) agreed with the theoretical exponent of 1.33, whereas Kim and Marshall (ref. 15) gave airstream relative velocity an exponent of only 1.14.

The exponent for airstream density is 0.67 according to theoretical analysis; in equation (8a) it is 0.4 and in the Nukiyama-Tanasawa expression it is zero. In other experimental results listed in table III the value of the exponent varies from 0.3 to 0.67. Thus the effect of airstream density on mean drop size needs to be investigated at higher airstream pressures than those used in this study.

The exponent of −0.4 given in equation (8a) for surface tension is close to the theoretical value of

-0.33 and to other experimentally determined values, which range from -0.33 to -0.5 in table III. The exponent of 0.4 given in equation (8a) for liquid density is also close to the theoretical value of 0.33; other experimental values range from 0.16 to 0.5 in table III. For liquid viscosity equation (8a) gives an exponent of -0.4, which agrees fairly well with other experimental values. These range from zero to -0.37 and are also considerably below the theoretical value of -0.67 given in equation (3a).

Concluding Remarks

The empirical correlation of mean drop size with the product of the Weber and Reynolds numbers, equations (7b) and (8b), gave relatively good agreement with theoretical expressions and other experimental correlations for both capillary and acceleration wave breakup. However, the agreements on the exponents for airstream density and liquid viscosity were not as good as might be expected. Thus the dimensionless group We Re may be just one of the factors effective in controlling mean drop size in capillary or acceleration wave breakup. Also, the equation for atomization in low-momentum airstreams, as derived in reference 2, was found to be valid for a number of different liquids (i.e., iso-octane, JP-5 fuel, benzene, carbon tetrachloride, and water). However, the equation for high-momentum airstreams was derived by using water jets only and should be tested for applicability to fuels and other liquids.

Summary of Results

Empirical correlations of reciprocal mean drop diameter with airstream momentum were derived from capillary and acceleration wave breakup of liquid jets atomized by cross-stream injection into axial-flow airstreams. A scanning radiometer was used to obtain data over an airstream momentum range of 3.7 to 25.7 g/cm^2 sec.

The results of this investigation were as follows:

1. Transition from capillary to acceleration wave breakup was obtained at a critical Weber-Reynolds number $(\text{We Re})_c$ of 10^6.

2. Values of We Re less than 10^6 produced a capillary wave type of atomization, and the ratio of orifice to mean drop diameter D_o/D_m was correlated with the Weber-Reynolds number product WeRe (i.e., $D_o/D_m = 0.21\ (\text{We Re})^{0.25}$).

3. Values of We Re greater than 10^6 produced an acceleration wave type of atomization conforming to the empirical expression $D_o/D_m = 0.027\ (\text{We Re})^{0.4}$.

4. For capillary wave breakup it was found that variations of the reciprocal mean drop diameter with airstream relative velocity could be expressed as $D_m^{-1} \sim V_r^{0.75}$. Theory predicted a relative velocity exponent of 0.67, which agrees within 10 percent of experimental results. Also experimental results gave $D_m^{-1} \sim D_o^{-5}$, which agreed with theory for capillary wave breakup.

5. For acceleration wave breakup it was found that $D_m^{-1} \sim V_r^{1.2}$. Theory predicted a relative velocity exponent of 1.33, or 10 percent greater than the experimental value. In the case of orifice diameter, it was found that $D_m^{-1} \sim D_o^{-0.2}$. This appeared to be more physically realistic than theory, which predicted no effect of orifice diameter on the reciprocal mean drop diameter.

6. Experimentally derived exponents for air density and liquid properties were in fair agreement with theory and the results of other experimental investigations. However, the effect of air-stream pressure on mean drop diameter should be investigated at high pressures.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 18, 1980

Appendix—Derivation of Theoretical Expressions for Liquid Jet Breakup

Ratio of Orifice Diameter to Critical Wavelength

Adelberg (ref. 11) expressed the critical wavelength L_c as

$$L_c = \left[\frac{\pi^3 \sigma D_j}{C_D(\sin^2\theta)^{1/2}\rho_a V_r^2} \right]^{0.5}$$

By assuming that the liquid jet diameter is approximately equal to the orifice diameter, $D_j = D_o$, and since $\mathrm{We} = \rho_a D_o V_r^2/\sigma$, the expression can be rewritten as

$$\frac{D_o}{L_c} = \left[\frac{2\pi^3}{C_D(\sin^2\theta)} \right]^{-0.5} \mathrm{We}^{0.5}$$

$$= 0.127 \left[C_D(\sin^2\theta) \right]^{0.5} \mathrm{We}^{0.5}$$

Capillary Wave Breakup

Adelberg (ref. 11) expressed capillary wave breakup as

$$D_m = 2.4 D_o^{0.5} \left[\frac{\mu_l(\sigma/\rho_l)^{0.5}}{\beta \rho_a V_r^2} \right]^{1/3} \times \left[1 - \frac{k\beta(\pi/2)^{0.5} e^{3/2}}{5J} \right]$$

By eliminating constants and substituting for the Weber number, the expression can be written as

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2} \right)^{1/6} \left(\frac{D_o \rho_a V_r^2}{\sigma} \right)^{1/3}$$

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2} \right)^{1/6} \mathrm{We}^{1/3}$$

Acceleration Wave Breakup

Adelberg (ref. 11) expressed acceleration wave breakup as

$$D_m = 65.3 \left[\frac{\mu_l(\sigma/\rho_l)^{0.5}}{\beta \rho_a V_r^2} \right]^{2/3}$$

By eliminating constants and substituting for the Weber number, the following relationship can be written:

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2} \right)^{1/3} \left(\frac{D_o \rho_a V_r^2}{\sigma} \right)^{2/3} \qquad (2a)$$

$$\frac{D_o}{D_m} \sim \left(\frac{D_o \rho_l \sigma}{\mu_l^2} \right)^{1/3} \mathrm{We}^{2/3}$$

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16. Abstract

Mean drop diameter data were obtained for liquid jet atomization by cross-stream injection from simple orifices into axial-flow airstreams. The data were used to derive empirical expressions for the atomization of liquid jets in the regimes of capillary wave breakup in low-momentum airstreams and acceleration wave breakup in high-momentum airstreams. Good agreement with atomization theory was obtained by correlating the ratio of orifice diameter to mean drop diameter D_o/D_m with the product of the Weber and Reynolds numbers WeRe as follows: $D_o/D_m = 0.21\,(\mathrm{WeRe})^{0.25}$ for $\mathrm{WeRe} < 10^6$ for capillary wave breakup and $D_o/D_m = 0.027\,(\mathrm{WeRe})^{0.4}$ for $\mathrm{WeRe} > 10^6$ for acceleration wave breakup. The Weber number is defined as $\rho_a D_o V_r^2/\sigma$ and the Reynolds number as $D_o V_r/\nu$, where V_r and ρ_a are airstream relative velocity and density, respectively, and σ and ν are surface tension and kinematic viscosity of the liquid, respectively. Transition from capillary wave to acceleration wave breakup occurred at $\mathrm{WeRe} = 10^6$.

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